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Technology Collaboration Programme

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Technology pathways used to produce SAF/biojet fuels:
Potential and challenges

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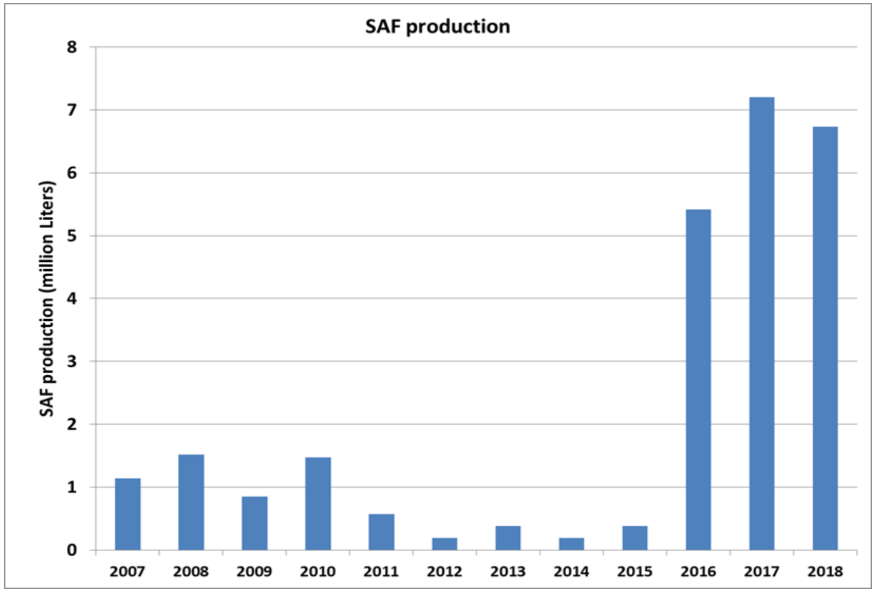
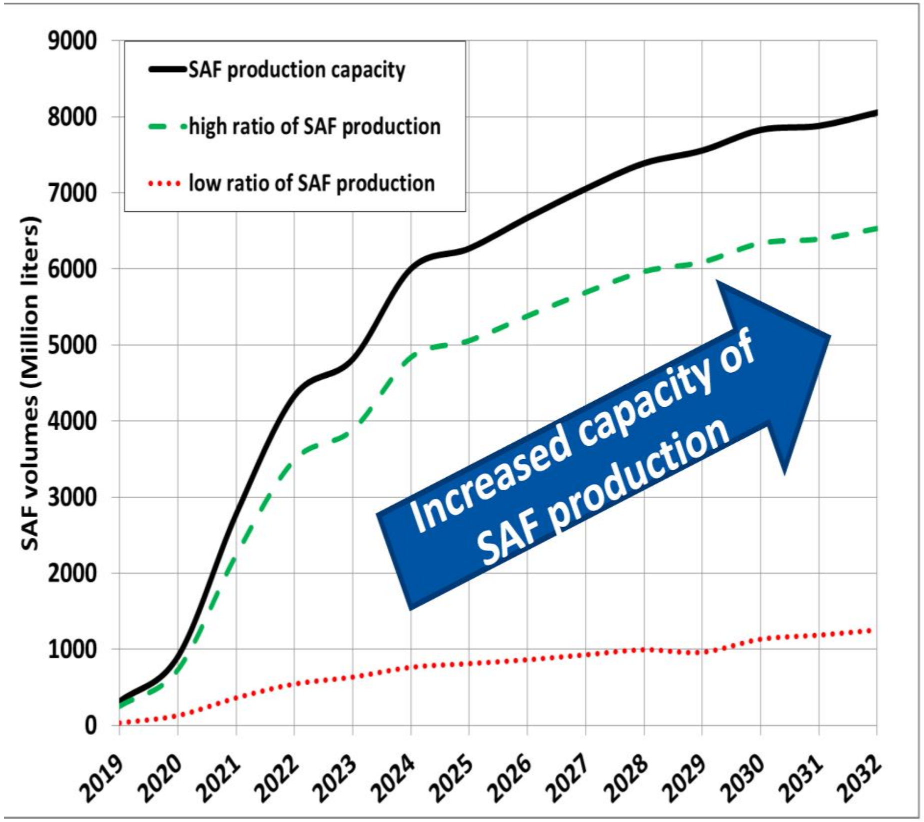
Current production volumes & future



Average of 0.29 million litres per year (2013-2015)
to 6.45 million litres per year (2016-2018).
In 2019 Neste produced 125 million litres



8 billion litres by 2032
<u>Far short</u> of volumes needed

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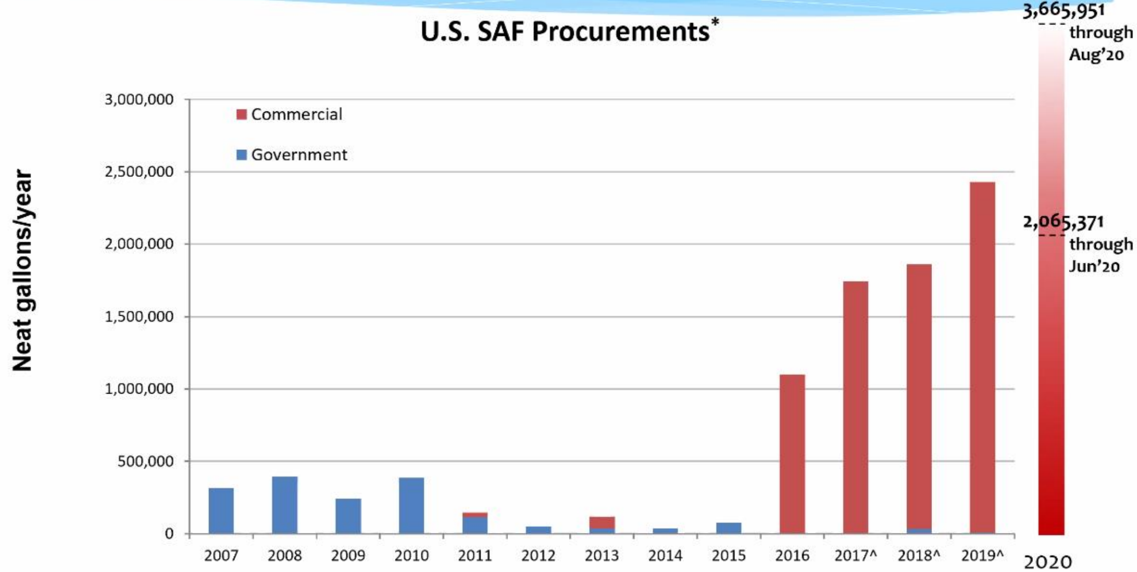
Status of U.S. SAF production / consumption
Initiation under way, still early

- Four years of sustained commercial use
- Commercial & General Aviation engaged
- Two facilities in operation
- Two facilities under construction, others in development
- Cost delta still a challenge, with policies favoring renewable diesel
- In spite of that … we still have $6.5 B in airline offtake commitments for >350M gpy … with more in development



Credit: FAA
*Reflects voluntarily reported data on use by U.S. airlines, U.S. government, manufacturers, other fuel users, and foreign carriers uplifting at U.S. airports.
^2017-2019 calculation includes reported EPA RFS2 RINs for jet fuel.

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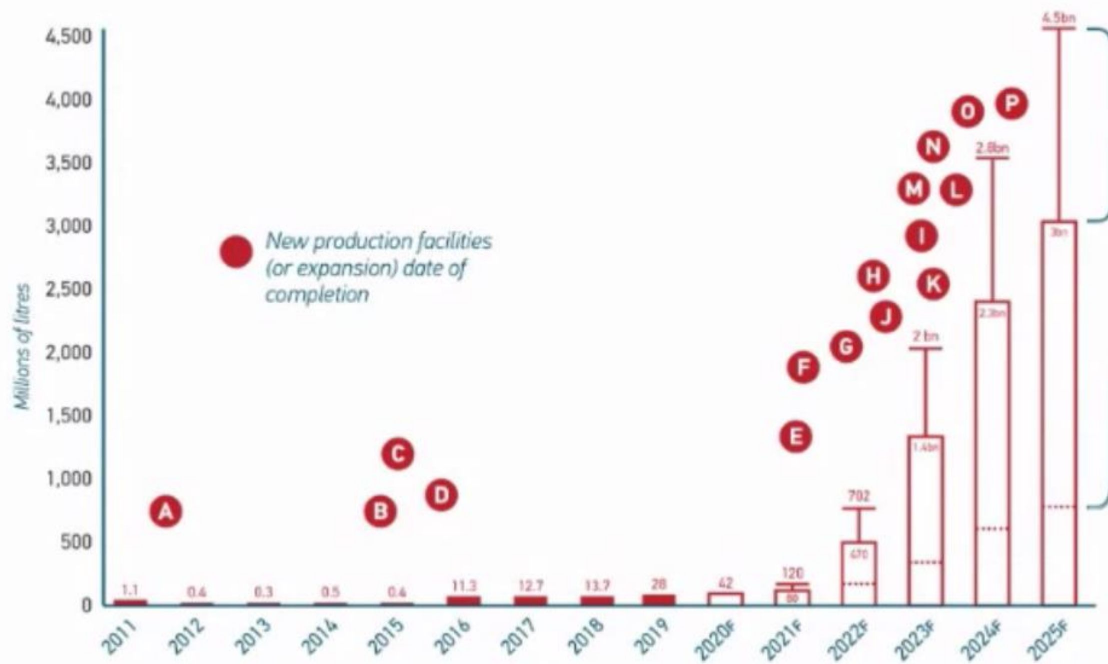
F Sustainable Aviation Fuel

What is the short-term deployment ramp-up of SAF?



Difference between a low take-up of SAF from production facilities *(lower number)* and a high take-up, driven by policy and airline decision-making. The top number represents the full possible output of SAF production already in operation, under construction or in advance planning and financing.

Without the correct policy measures, the fuel output could be optimised to go to other forms of transport – the lowest dotted line represents the least uptake of SAF (output goes to road transport).

This analysis does not include SAF capacity that has not yet been announced, is in concept stage, nor the impact of aggressive policy support which could double the potential by 2025.

- **A** Neste (Singapore / Finland)
- **B** Gevo (USA)
- **C** Amyris (Brazil)
- **D** World Energy (USA)
- **E** World Energy (USA)
- **F** Fulcrum (USA)
- **G** Neste (Singapore)
- **H** LanzaTech (North Asia)
- **I** SkyNRG (Netherlands)
- **J** UPM (USA)
- **K** Red Rock (USA)
- **L** Total (France)
- **M** Diamond Green (USA)
- **N** REG (USA)
- **O** Preem (Sweden)
- **P** Velocys (UK)

www.aviationbenefits.org

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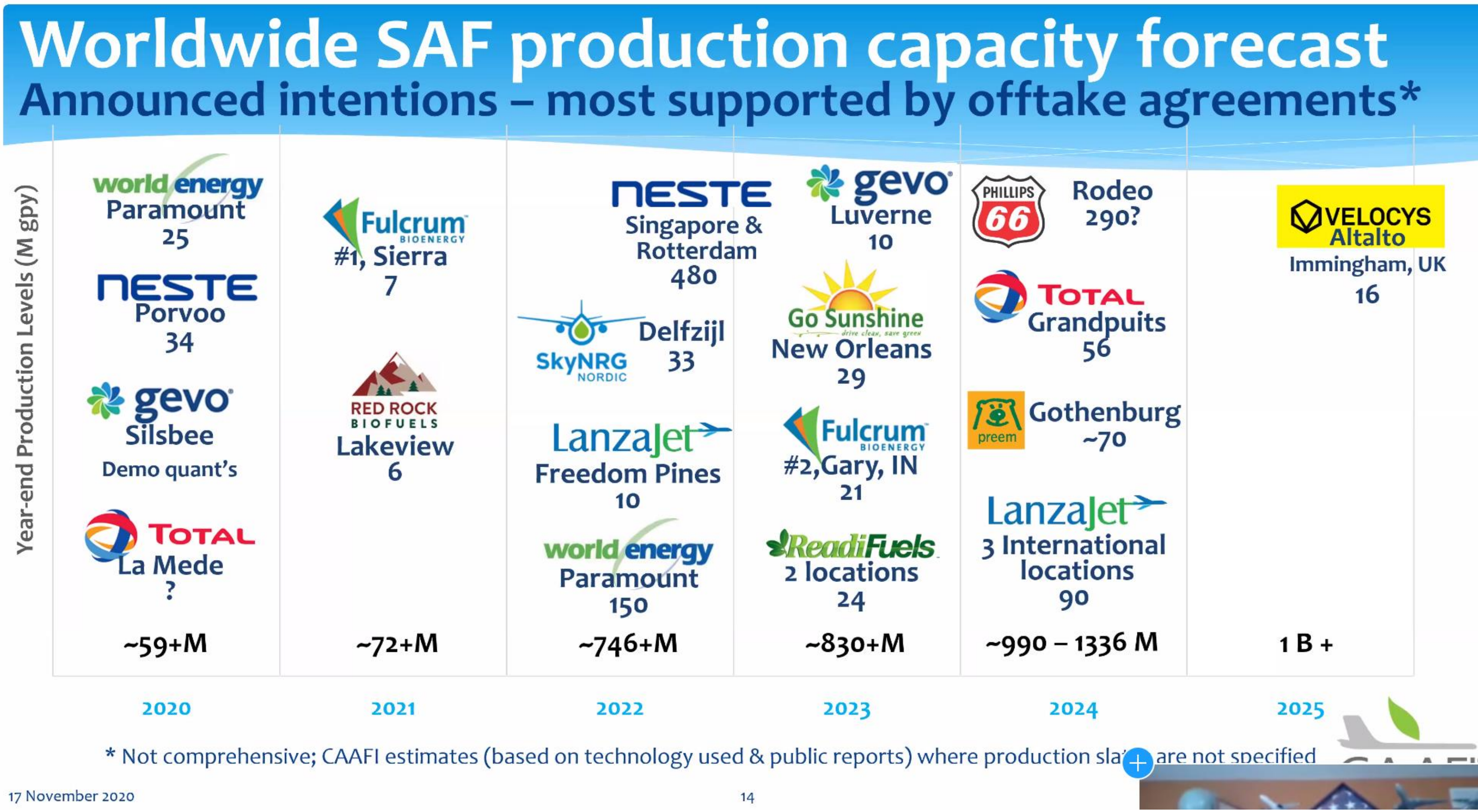

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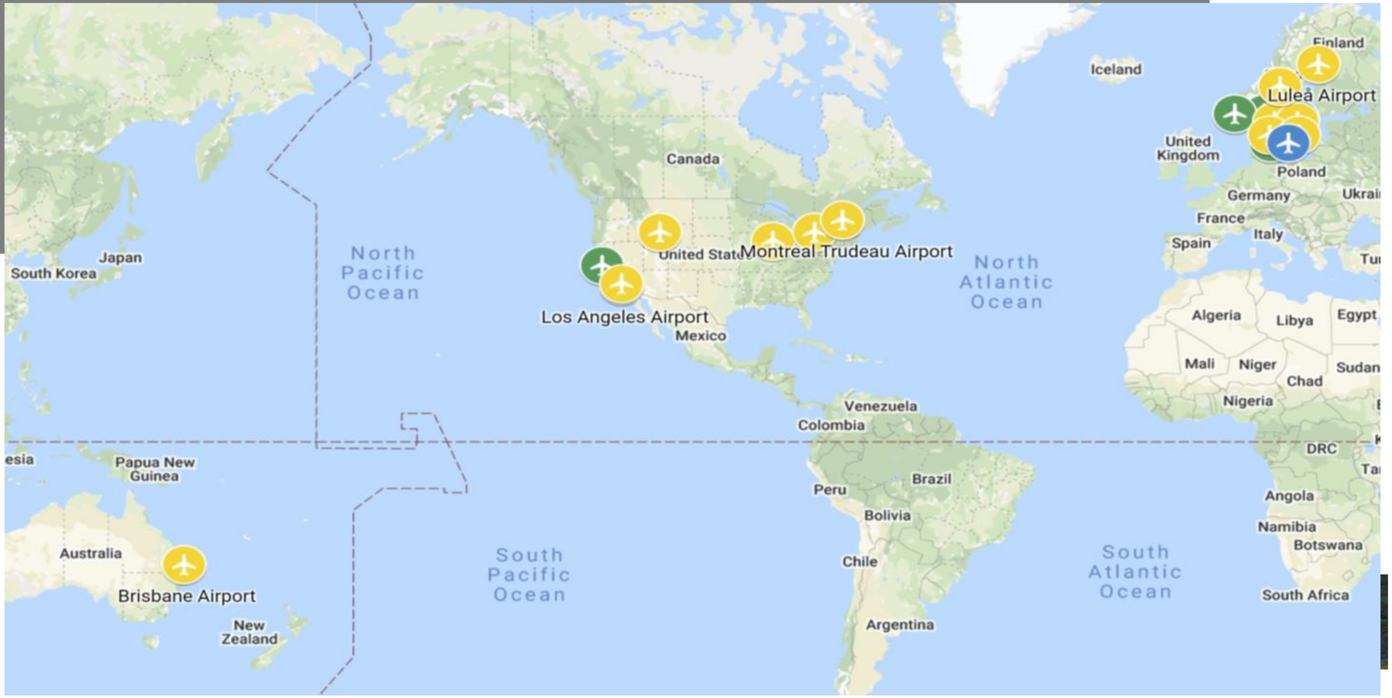
Alternative fuel use at airports

Batch delivery
Karlstad Airport
Chicago O'Hare Airport
Brisbane Airport
Toronto-Pearson Airport
Montreal Trudeau Airport
Stockholm Broma Airport
Åre Östersund Airport
Göteborg Landvetter Airport
Visby Airport
Luleå Airport
Van Nuys Airport
Jackson Hole Airport

Ongoing deliveries (Offtake agreement)
Los Angeles Airport
Oslo Airport
San Francisco Airport
Stockholm Arlanda Airport
Bergen Airport
Vaxjo Smaland Airport
Halmstad Airport

Planned deliveries
Kalmar Öland Airport



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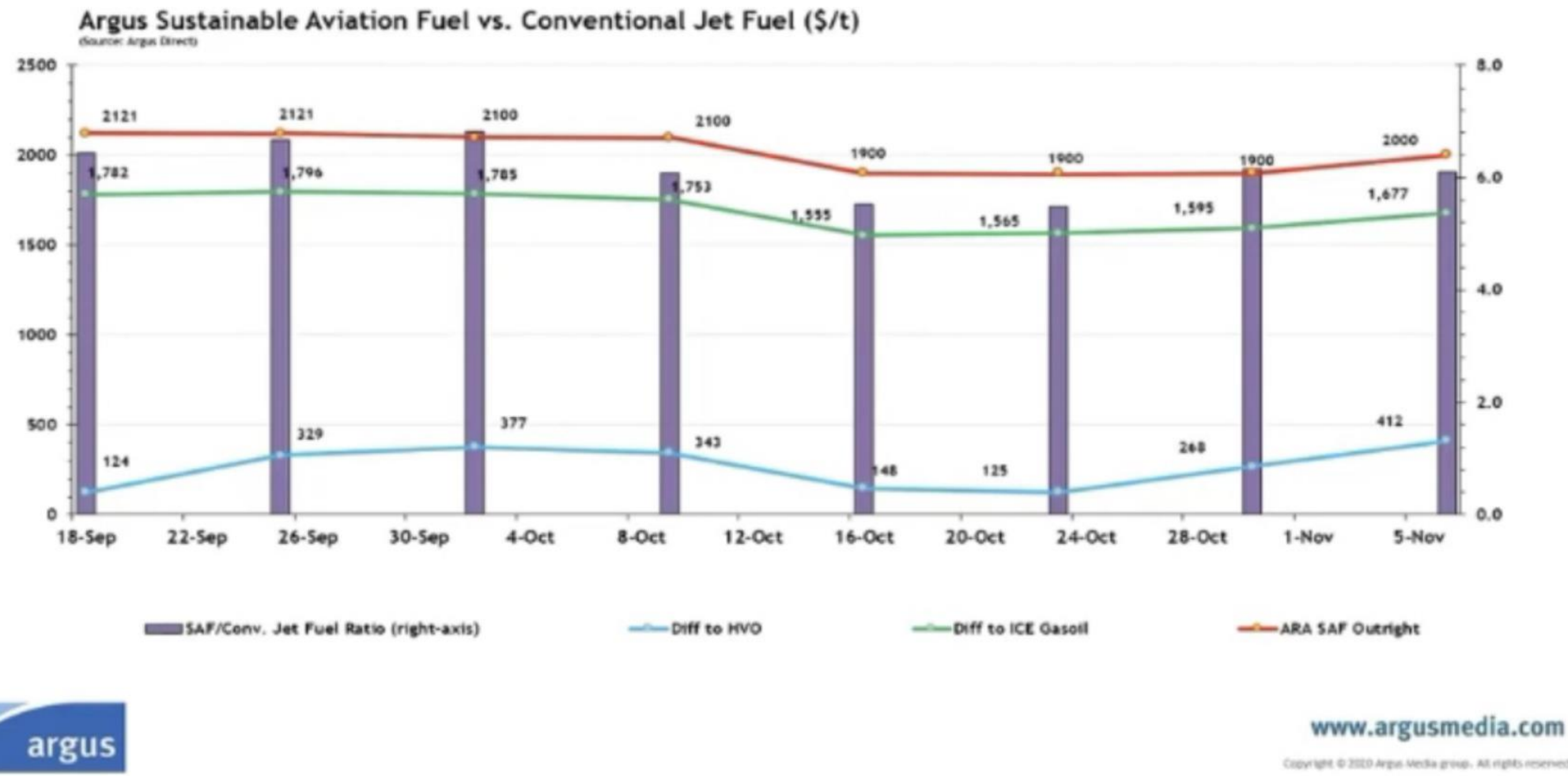
Mandates

- 2020 – Norway mandate of 0.5% SAF
- 2030 – Norway mandate increases to 30%
- 2021 – Sweden proposal for 0.8% emissions reduction obligation for domestic jet fuel
- 2030 – Sweden mandate for 27% reduction in emissions
- 2035 – Finland targets 30% SAF in aviation

SAF vs. Conventional Jet vs. HVO and Gasoil



Conventional jet fuel assessed at $329.25/t on 18 September, more than six times lower than SAF, which was valued at $2,124.47/t (Argusmedia.com)

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Technology platforms – certification and commercialisation

- ASTM certification of pathways

APPROVED

- Fischer-Tropsch SPK & SKA (2009) (50%)
- HEFA SPK (2011) (50%)
- Synthesized Iso-paraffins (SIP) (2014) (10%)
- Alcohol to jet SPK (isobutanol(2016), ethanol (2018))
- Catalytic hydro-thermolysis of lipids to jet fuel (50%)
- HC-HEFA-SPK – lipids from *Botryococcus braunii* algae (10%)
- Co-processing of lipids (5%)

In progress

- Synthetic kerosene/synthetic aromatic kerosene – Shell/Virent
- HEFA+ - HEFA with improved cold flow properties – Boeing
- Pyrolysis from lignocellulosic feedstocks – UOP, Kior (stalled)
- & 15 others in pre-certification stage

Hydrotreated esters and fatty acids - synthetic paraffinic kerosene (HEFA-SPK)

- Trends
  - Significant expansion of standalone facilities
  - Separation of the jet fraction in existing facilities (Neste/World Energy/etc.)
- Opportunities
  - ASTM certified & commercial scale
  - With limited investment, every current HEFA (renewable diesel) facility can potentially produce ~15% biojet, significantly expanding volumes
  - Improvement in sustainability by using "waste" feedstocks (e.g. UCO)
  - Favourable policies can boost investment into technology/feedstocks.
- Challenges
  - Cost, availability & sustainability of vegetable oils
  - Availability will limit the maximum production of HEFA
  - Competition with renewable diesel that gets significant policy support
  - Renewable diesel cheaper to make
  - Limited scope for technical improvements (reducing hydrogen consumption)

Gasification and Fischer-Tropsch (FT-SPK)

- Trends
  - Current facilities under construction
- Opportunities
  - Can use waste feedstocks such as MSW & forest residues
  - ASTM certified
  - Co-processing of FT liquids
  - Catalyst improvement to increase the jet fraction
- Challenges
  - Very high capital cost
  - Commercialisation very slow
  - Economies of scale difficult
  - Syngas cleanup – complexity and cost, while feedstocks have variable contaminants

Direct thermochemical liquefaction (HTL, Fast Pyrolysis, Catalytic pyrolysis)

- Trends
  - Ongoing work into upgrading
  - HTL has garnered increased interest for biojet production
- Opportunities
  - Potential for co-processing
  - Cheaper, sustainable and more feedstock available
  - HTL can use a variety of wet feedstocks – sewage, food processing waste, plastics
- Challenges
  - Complexity of biocrudes & variation with type of feedstock
  - Upgrading - technical challenges, catalyst inhibition, (e.g. cost and lifespan), availability for trials, etc.
  - Not ASTM certified
  - Other aspects (e.g. interest by oil companies, etc.)

Alcohol-to-jet (ATJ-SPK)

- Trends
  - Isobutanol to jet delivering small commercial volumes
  - Lanzajet technology scaling up
- Opportunities
  - Lower infrastructure cost as ethanol facilities can be repurposed and organisms substituted (e.g. butanol)
  - Genetic modification of strains for higher yields
  - Potential to use low-cost waste gases for ethanol production
  - High % of jet fraction (70%)
  - Established ATJ technology
- Challenges
  - Cost of alcohol production
  - Higher value of alcohol intermediate for other (fuel, feedstock, etc.) applications
  - Use of cellulosic feedstocks for alcohol production unlikely

Power-to-Liquids

- Trends
  - Current high interest

- Opportunities
  - Significant emission reductions
  - Does not use biomass feedstocks or need arable land
  - Could have “electricity grids” as partners

- Challenges
  - Not feasible without renewable energy
  - Competition with other renewable energy applications that may be cheaper – heat, electricity, road transportation
  - Very high cost of direct air carbon capture
  - Still at the initial stage of development
  - Generally considered to be a long-term option

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Other technologies

- Farnesane SIP-SPK
  - High value product and unlikely to produce biojet
  - High cost of technology

- Catalytic hydrothermolysis (lipids)
  - Competition for feedstock with HEFA

- HEFA+ / Low freezepoint HEFA
  - ASTM process has stalled

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Conclusions

- Many biojet technologies have received ASTM certification and are being commercialized
- But HEFA provides the only substantial commercial volumes – will continue to be the main technology for the next 5-10 years
- With limited investment all renewable diesel facilities can produce at least 15% biojet fraction or more
- Multiple technologies based on multiple feedstocks are required to deliver 100-200 billion litres by 2050
- Technical challenges remain, but high investment cost and high price difference with conventional jet fuel remains the biggest obstacle and only policy can overcome these obstacles

Thanks!

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